Tiled++
An Enhanced Tiled Hi-Res Display Wall

Achim Ebert, Sebastian Thelen, Peter-Scott Olech, Joerg Meyer and Hans Hagen, *Life Fellow, IEEE*

Abstract—In recent years, high-resolution displays have become increasingly important to decision makers and scientists, because large screens combined with a high pixel count facilitate content rich, simultaneous display of computer-generated imagery and high-definition video data from multiple sources. Tiled displays are attractive due to their extended screen real estate, scalability, and low cost. LCD panels are usually preferred over projectors because of their superior resolution. One of the drawbacks of LCD-based tiled displays is the fact that users sometimes get distracted by the screens' bezels, which cause discontinuities in rendered images, animations, or videos. Most conventional solutions either ignore the bezels and display all pixels, causing objects to become distorted, or eliminate the pixels that would normally fall under the bezels, causing pixels to be missing in the display of static images. In animations, the missing pixels will eventually reappear when the object moves, providing an experience that is similar to looking through a French window.
In this paper we present a new scalable approach that neither leads to discontinuities nor significant loss of information. By projecting onto the bezels, we demonstrate that a combination of LCD-based tiled displays and projection significantly reduces the bezel problem. Our technique eliminates ambiguities that commonly occur on tiled displays in the fields of information visualization, visual data analysis, and scientific data display. It improves the usability of multi-monitor systems by virtually eliminating the bezels. We describe a setup and provide results from an evaluation experiment conducted on a 3 $\times$ 3 and on a 10 $\times$ 5 tiled display wall.

Index Terms—Tiled Displays, Computer Projector, LCD Panel, Bezel, High-Resolution Displays.

1 Introduction

Whenever two or more people gather in front of a commodity computer screen, it becomes obvious that single-user desktop displays have certain limitations due their limited screen size. Therefore large displays have become widely used as the medium of choice for presentations. Due to recent price drops, large screens have made their way into conference rooms and are commonly used for public displays, e.g., for advertising and signage. Extensive user studies have shown that the efficiency of users when presented with visual tasks is affected positively by an extended amount of screen real estate [1], [2], [3], [4]. This has been proven to be the case in particular for 3D navigational tasks [5], [6], [7]. The use of a projector or a large LC display can help to overcome the screen size problem to some extent, so that multiple users can view the same content on a single display. Nevertheless, the size and resolution of such displays is still limited. This lead to the obvious solution of combining multiple display devices and to use computer software to make them appear as one large logical display. Especially applications in scientific and information visualization benefit from this approach, because these fields often require the display of complex, high-resolution data sets, which frequently cannot be displayed on a single monitor. Two categories of display technologies can be identified:

1) Multiple projectors can be combined to form a **projector-based** tiled display. The challenge lies in calibrating the system, as projector images are usually distorted and non-uniform in terms of color and luminance. The overall resolution of these systems is medium to high, depending on the projectors being used.
2) LCDs represent the most affordable way of building a large high-resolution display. **LCD-based** systems are easier to set up than projector-based systems, since they usually do not require as much space and problems like lens distortions and deviations in luminance or color temperature do not arise or only occur to a much lesser extent.

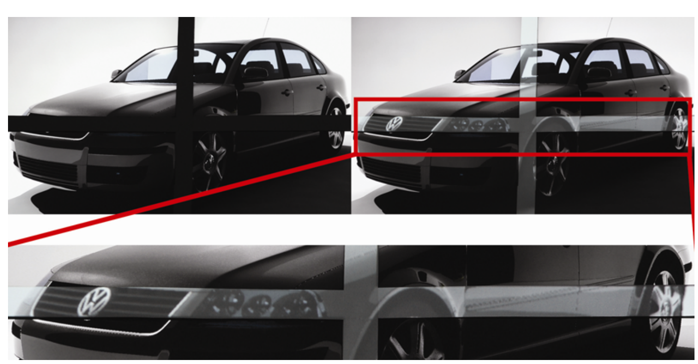


Fig. 1. Tiled++ providing *important* image information.

- A. Ebert is with the Department of Computer Science, Technical University of Kaiserslautern, Germany and with the Competence Center Human-Centered Visualization, German Research Center for Artificial Intelligence (DFKI), Germany.
E-mail: ebert@informatik.uni-kl.de
- S. Thelen, P. Olech and H. Hagen are with the Department of Computer Science, Technical University of Kaiserslautern, Germany.
E-mail: {s_thelen, olech, hagen}@informatik.uni-kl.de
- J. Meyer is with the University of California, Irvine, USA.
E-mail: jmeyer@uci.edu

Manuscript received August 1, 2008; revised July 24, 2008.

> Further the resolution of today's average LCDs is higher than the one of most projectors, so that it is relatively easy to build systems with a resolution of several gigapixels.[1]

Developing these systems has become possible through latest advances in display and hardware technology. Driving tiled displays requires powerful graphics hardware supporting high resolution (e.g. 2560×1600 pixels per monitor), fast CPUs for computing complex scenes and high-speed network connections for distributing data across rendering nodes. Altogether tiled displays are more popular than ever, which makes them an attractive research topic for the future. In this context Ni et al. [8] came up with a list of what they believe are the top ten research challenges in the area of high-resolution displays. Number one on their list is the creation of *truly seamless tiled displays*. Quite a lot of work has been done on image blending, geometric registration, and color- and luminance matching of projector-based systems [9]. However, discontinuities are an inherent problem of LCD-based systems caused by the bezels of monitors interrupting the scene.

In this paper we focus on LCD-based multi-monitor systems and make a contribution to address the bezel problem, i.e., to fill in the missing information under the bezels. For many applications data is continuous and correct spatial relationships are needed to interpret information in the right way. Here monitor bezels can be very distracting and interfere with the objective of providing precise visualizations of the data. Our approach is to enhance the bezel area with image information using additional projectors. This means we project the missing image information directly onto the bezels. Thereby we create a nearly seamless image, which is composed of the high-resolution information displayed on the monitors and somewhat lower resolution information projected onto the bezels to fill the gaps (Fig. 1). In the following we provide an overview of related work, explain the bezel problem in detail and introduce our **Tiled++** framework and its benefits for a nearly seamless tiled display. We conclude with results from a user study we conducted in order to evaluate the effectiveness of our approach.

2 Related Work

With the building of tiled display systems one tries to solve the problem of screen real estate combined with a moderate to high resolution, where regular single device resolutions reach their limits.

Within the research area of tiled displays there have been several interesting approaches, for both projector-based and monitor-based tiled display systems. In this section we want to give an insight to some important research aspects.

By using multiple projectors one bypasses the bezel problem associated with LCD-based systems, but has to cope with several other issues. The calibration of projectors is a major challenge in setting up a really seamless system. In the following we present selected publications addressing these problems.

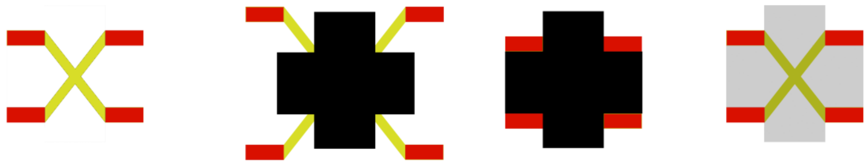
One challenge in the geometric alignment of projectors is the minimization of the *keystone effect*. Keystone effects are distortions of the image caused by attempting to project onto a surface at an angle, so that the projector is not centered onto the screen. Sukthankar et al. [10] presented a setup to compensate the effect for single-projector systems. The system is able to self-calibrate with the feedback obtained from a *camera*. The projector is set up to project even on all sides and to produce a keystone-free image. In the following, their method was refined for the use with multiple projectors [11].

A similar approach, using an un-calibrated camera to measure the mismatches between neighboring projectors, was previously presented in the work of Chen et al. [12]. The authors use a two-stage automatic alignment algorithm. In stage one, the misalignment measurement stage, a camera observes point and line matches between neighboring projectors. Stage two, the alignment computation stage, sets up and solves a multi-dimensional global minimization problem based the camera observations from stage one as its constraints. With this approach the authors were able to calibrate a tiled wall system with up to 24 projectors.

Another major problem is the calibration of projectors in regard of their brightness and color. An overview to color and brightness issues was given in the paper of Stone et al. [13], whereas an approach to solve these issues was presented by Majumder et al. [14]. The photometric non-uniformity between different projectors was corrected by using channel look-up-tables. A real-time photometric correction was applied to the projectors using a spectroradiometer to match the colors. In the following, Majumder et al. presented a perceptual photometric seamless tiled display, using a camera and a photometer [15]. In this publication the authors demonstrated that perceptual criteria are effective for receiving perceptual photometric uniformity in projector-based tiled display systems.

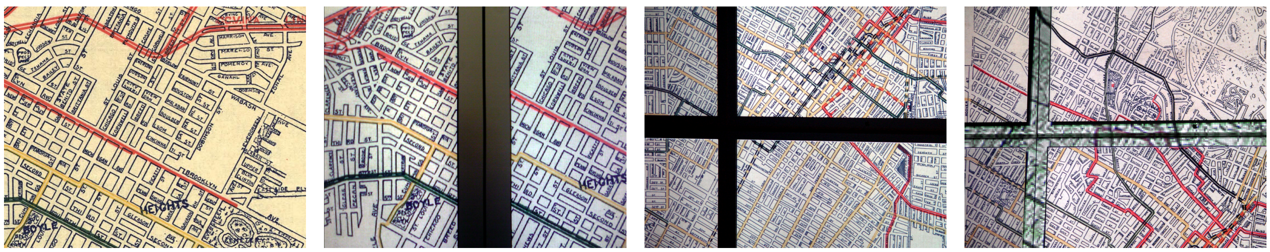
When using front projection-based setups, shadowing is another major issue. Presentations can be disturbed by objects entering the projection area and casting shadows. Jaynes et al. [16] addressed this problem in 2001. The authors solve the shadow problem in screen space by the use of cameras comparing the image being displayed to an expected reference image. Points of the display have to be illuminated by at least two projectors, so that shadowing of one projector can be compensated by the second one. Sukthankar et al. [17] also addressed the shadow problem of front-projection based systems. They solve it by mounting multiple projectors at different

1. Display resolution is typically measured in ppi [pixels per inch]. For a more intuitive approach we have chosen pixel count as our metric, because it is independent of the physical size of the display and mainly describes the amount of information the screen is capable of displaying.



(a) (b) (c) (d)

Fig. 2. Semantic problems: a) original scenario, b) discontinuities due to the offset approach (image looks distorted/expanded), c) overlays hide the crossing (missing pixels), d) missing information provided by Tiled++.



(a) (b) (c) (d)

Fig. 3. HIPerWall (200 megapixel tiled display wall): a) original image (Los Angeles Railway System of 1906), b) discontinuities due to the offset approach (diagonal lines appear to be disconnected or incorrectly aligned), c) overlay mode (pixels under bezels have been eliminated, leading to missing information), d) missing information provided by Tiled++. (Images courtesy of Library of Congress, Division of Maps.)

locations. A camera is used to identify occlusions when they appear and to adjust the amount of light projected to each occluded part of the image. The system is self calibrating.

For monitor-based tiled displays there have been several approaches trying to minimize or bypass the bezel problem. In the work of Mackinley et al. [18] the bezel problem of the wideband display was approached by presenting novel interface techniques and seam aware applications. In the paper of Ball et al. [1] parts of the monitor frame were physically removed to minimize gaps between neighboring displays. Most other publications do not explicitly deal with the bezel problem and accept all consequences of monitor frames passing the display.

The bezel problem implies other challenges when setting up monitor-based tiled systems. For navigation tasks it is necessary that the pointer can cross monitor bezels when moving from one display to another without irritating the user. Baudisch et al. [19] compensate offset and warping effects by applying appropriate transformations to the movement of the cursor. The approach even works for multi-monitor systems having non-uniform screen resolutions.

Another interesting application with a certain relevance to our approach is the focus + context screen [20]. In the focus + context screen a large low-resolution area coming from a projector, is used to display context information. A small high-resolution screen integrated into the context area displays detailed information of the current focus. The combination of different display technologies is what makes the focus + context screen resemble the approach we are going to present.

2.1 The Bezel Problem

The bezel problem of LCD-based tiled displays is caused by monitor frames that pass the screen and disturb the impression of a seamless display. Unfortunately these frames a still a necessity for modern LCDs and bezel-free displays are not available at the present. The frames contain control elements that are needed to drive the display. Monitors with minimal bezel areas can reduce their effect in tiled displays but sill the lattice they create is one of the major disadvantages of the LCD-based approach. Usually there are two ways of dealing with this problem:

1) The **offset approach** simply ignores the bezels and their effect on the continuousness of a scene. A mouse cursor crossing the border of one monitor jumps into the neighboring one and objects in that region appear to be stretched by an offset that is equal to the bezel size of monitors plus the distance between them. This can create strange effects and seems to be intolerable at a first glance. However the offset approach has the advantage that no image information gets lost at the monitor borders.
2) The **overlay approach** tries to compensate the bezel problem by pretending the lattice to be an overlay of the image. In contrast to the offset approach mouse cursors and other objects will vanish under the bezels. The result is an overall continuous

image with one having the impression of looking through a window with vertical and horizontal bars. While this seems to be preferable to the discontinuities that are caused by the offset approach, one has to keep in mind that potentially important information can be "hidden" by the bezels.

Both approaches come along with their own advantages and disadvantages. A choice between them depends on the particular application. In any case the perception of a scene will be affected by the technique being used. We would like to refer to this circumstance as **loss of semantics**. Fig. 2 depicts what we mean by this:
In an electric circuit visualization the crossing of two wires will result in images as shown in Fig. 2(b) and Fig. 2(c) under the two approaches. With the offset approach an engineer will still be able to recognize what is happening, although he will have to keep in mind that the image is actually distorted. The overlay does not even give him a clue of the crossing. This is a potential source for failures.
Fig. 3 shows the same scenario in a real world application. The image shows a map of the Los Angeles Railway System of 1906 displayed on HIPerWall, a 200 megapixel tiled display (10 x 5 LCDs, 30 inches diagonal each). As with most roadmaps, the image contains many horizontal, vertical and diagonal lines. Using the offset approach (Fig. 3(b)) leads to misinterpretations, because the human brain tends to extend lines that are invisible in a straight line and assumes that a line on the other side of the bezel that is in the same line of sight must be connected, which is not the case here. In fact, since many streets on the map run parallel, the brain tries to connect roads that are not really connected. In Fig. 3(c), the pixels under the bezels have been removed, assuming that the bezels serve as an overlay which covers these pixels and renders them invisible. Fig. 3(d) shows how the missing context information can be provided by projecting directly onto the bezels. The bezels are made of brushed aluminum and were not modified from the original manufacturer's specification. The figure shows a dramatic improvement in providing sufficient context leading to a correct interpretation of the information contained in the image.
Another, more subtle effect can lead to additional misinterpretation when using the overlay approach. In neurosciences it is known that two collinear oblique lines separated by two vertical parallels can cause failures of perception. The collinear lines appear to be offset, even if in fact they are aligned (Fig. 4). This effect was first discovered in 1860 by the physicist J. C. Poggendorff and is therefore named **Poggendorff Illusion**. Although the reasons for the effect are not yet well understood, it has an impact on the visualization with LCD-based tiled display, for Poggendorff situations arise at the interface between two monitors. In the evaluation section we will closer examine the effect on the performance of users.
Further influences of the approaches can be characterized by Ware's [21] classification of preattentively processible features. Ware defined four categories of optical attributes whose visual identification is performed in a very short time lapse: color, movement, spatial localization and form. Especially form features, such as line length, line collinearity, size and spatial grouping are affected by the described solutions and demand for a precise evaluation.

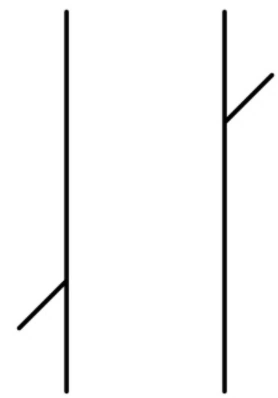


Fig. 4. The Poggendorff illusion. Alltough both oblique lines are in fact collinear, they appear to be offset.

We want to combine the availability of all pixel information (offset) with the continuousness of the whole scene (overlay) and present a technique that neither distorts objects across the boundary of monitors nor covers important information without giving a hint of what is happening beneath the bezels. The following section describes the idea of our approach.
The goal is to represent the situation shown in Fig. 2(a) correctly, i.e., the Tiled++ approach will produce results as sketched in Fig. 2(d). The crossing will be visible without distortions or full loss of pixels. The enhanced bezels will provide the otherwise hidden information in a lower resolution and prevent misinterpretation in that region.

3 Enhancing the Tiled Display

3.1 The Tiled++ Approach

The bezel problem can be reduced by using thin-framed monitors. The screens of our tiled display have bezels of approximately one inch size, so that we have to cope with offsets of about two inches between neighboring monitors (gaps caused by the monitor rack can increase the offset). We make a virtue out of this necessity and use the monitor frames as display areas for additional projectors. The monitors display the scene treating the bezels as overlays while at the same time missing information is provided by the projectors. The projectors only render those parts of a scene that would be hidden by the lattice (Fig. 5). Black monitor bezels a barely reflecting and not suited for projecting directly onto them. We

bond the frames with diffuse reflecting white cardboard and create a lattice-like reflective screen as illustrated in Fig. 6. For the 10 $\times$ 5 configuration, no changes were necessary, as the bezels are made of brushed aluminum, which provides a perfect silver screen for projection (Fig. 7). The image parts displayed on the lattice provide missing information in a projector dependent resolution (e.g. 1920×1080) which is lower than that of the monitors (e.g. 2560×1600), so that the whole scene can be divided into regions of very high and rather low resolution. When using more than one projector each of them can be restricted to a predefined subset of monitors. Thereby the lattice resolution is increased.
The described combination of projectors and LCDs is new to our knowledge. Although high-resolution and low-resolution devices have been used together previously, e.g. in the focus+context screen [20], it has never been done with the intention of solving the bezel problem.

3.2 System calibration

In this section we describe the calibration process of a Tiled++ system, which basically involves two steps:

1) Determining the **geometry of the display wall** by measuring the location, size and rotation of every monitor. The information is made available to our render framework.
2) **Calibrating the projectors** to cover a certain lattice area of the display wall and to align them seamlessly with each other.

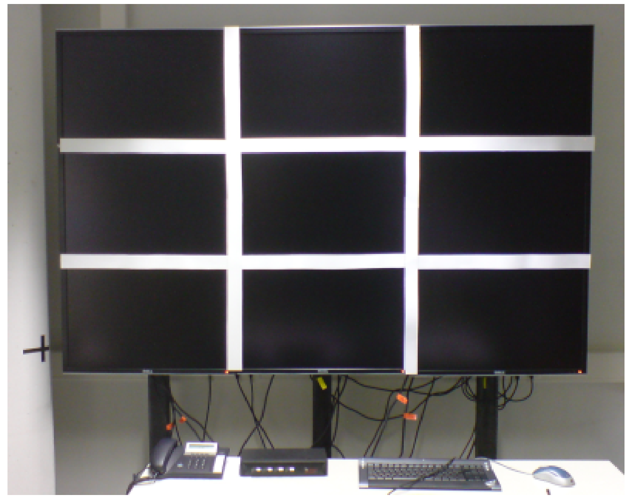


Fig. 6. A 3 $\times$ 3 Tiled++ setup (white bezels).

Fig. 7. A 10 $\times$ 5 Tiled++ setup (aluminum bezels).

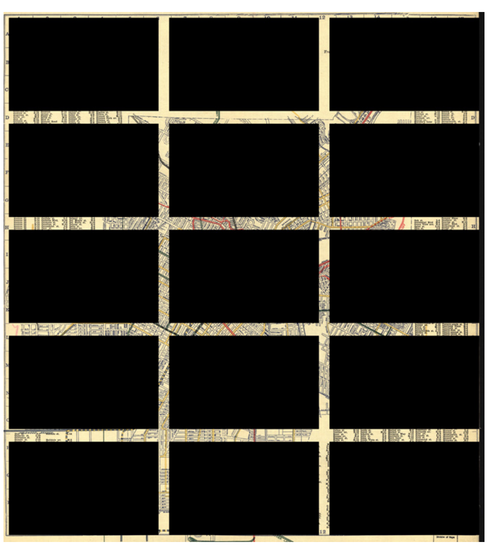
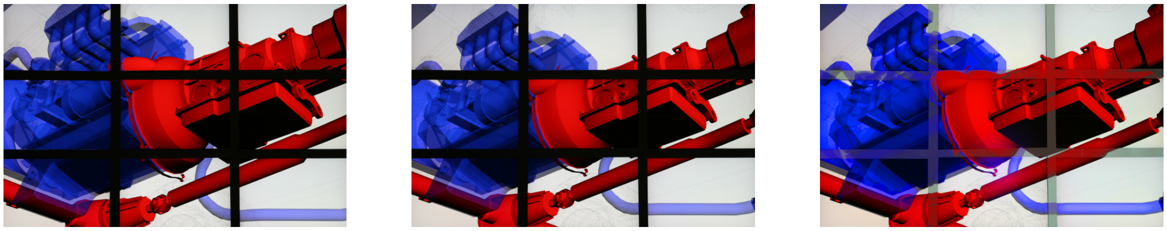


Fig. 5. Low-resolution (about 10% of the original resolution) image information is projected only onto the bezel lattice. The areas of the backlit LCD panels are blacked out. (Sections of Los Angeles Railway Map.)

Our framework for driving the displays and projectors is designed to be highly configurable and flexible. We do not want to rely on a fixed installation and therefore take the geometry of the display cluster as an input to our framework. We measure the location, dimension and rotation of every single monitor with the help of a camera using standard image processing techniques and store all values in a configuration file. The parameters tell the framework which cut-out of a scene is to be shown on which LCD and which parts are to be hidden under the bezels. Furthermore the framework knows which parts are to be displayed by the projectors. Since the projectors only provide low-resolution information, they cannot project directly onto the high-resolution areas of the LCDs. Their contribution has to be restricted to the lattice in order to avoid confusion. Knowing the geometry of the display wall helps the framework in doing so. The projectors only render on the silver screen and mask the LCD areas with black quads. We found that projectors with good black light properties can improve the overall quality of a scene.
There exist various methods for aligning projectors in terms of geometry, luminance and color. In principle every known technique for the calibration of multi-projector systems can be applied. However, since we focus on the Tiled++ approach in general and not on a fully sophisticated implementation we restrict ourselves to the *geometric* alignment of projectors to a certain cut-out of the display wall, knowing that additional techniques can be applied to make the transition between



(a) (b) (c)

Fig. 8. A CAD example demonstrating the advantages of Tiled++: a) Strong discontinuity effects with the offset approach disturb perception, b) With overlay approach image information is *occluded* under the bezels, c) Tiled++ offers *superior perception* outranging the two competitive approaches.

projectors and LCDs as seamless as possible. We want to be able to place projectors at arbitrary positions in front of the displays. The problem that occurs is that, that the image of a projector placed non-perpendicular to a screen will be trapezoidally distorted. This effect, commonly known as *keystoning*, must be considered whenever precise results are sought. Modern projectors come with built-in keystone corrections that distort the images in such a way that keystoning is compensated. Unfortunately built-in corrections are too coarse for our purpose, which is why we have to implement our own, improved method.

Homographies are mappings in the two-dimensional projective space that preserve collinearities of points and concurrencies of lines. A homography is uniquely defined by four 2D point pair correspondences $\{L_i \leftrightarrow R_i\}_i$ and is computed by determining the coefficients $\{h_{ij}\}_{i,j}$ of a 3×3 homography matrix H, so that $R_i = H \cdot L_i$. Homographies map points of one quadriliteral to corresponding points of a second quadriliteral, which is exactly what is needed for keystone correction. We determine correspondences with help of a captured video image and solve a system of linear equations to obtain the entries of the homography matrix H. Finally we combine H with OpenGL's projection matrix and distort the projector image so that keystone effects are compensated for.

3.3 Protoype Systems

Tiled++ was installed on two prototypic systems of different sizes. The smaller one consists of 5 commodity PCs driving a 3×3 tiled LCD wall (Fig. 6). All nodes of the cluster are connected via Ethernet and contain Intel Core2 Duo CPUs with 2.40 GHz, two dual GPU GeForce 7950 GX2 graphic cards with 1024MB RAM (512 per GPU) and 2GB main memory. 30 inch DELL UltraSharp 3007WFP monitors achieve a resolution of 2560×1600 pixels and have bezels of approximately one inch size. The LCDs achieve a combined resolution of 7680×4800 pixels. Monitor frames are enhanced by a NEC HD projector with 1920×1080 resolution.

With the second system we tested the scalability of Tiled++ (see section 3.4). The HIPerWall is a 200 megapixel tiled display with a resolution of 25600×8000 pixels. The fifty Apple Cinema Displays are arranged in a 10×5 grid and are driven by 25 Power Mac G5 computer nodes. A designated additional node is responsible for managing high-level display functions.

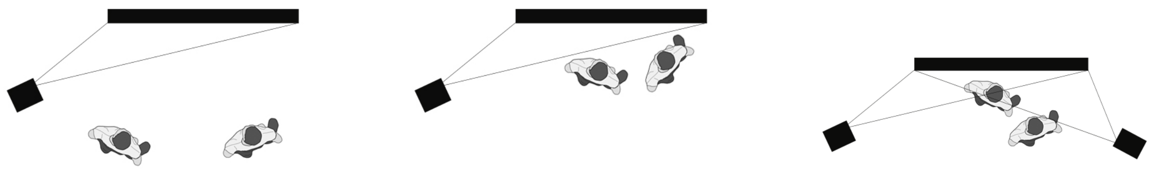
The render framework for driving the system is implemented in C++ and OpenGL and uses MPI (Message Passing Interface) for managing synchronization and communication between executing threads. Window and event handling is done via SDL (Simple Direct Media Layer). All software is open source and thus supports portability to different platforms. The framework is a *master-slave* system [8], i.e. all nodes execute an instance of the application while a dedicated node - the master - is responsible for processing user input and making it known to the slaves.

3.4 Scalability

The Tiled++ system is scalable, as demonstrated on our two different display configurations. Multiple projectors can be used to fill the entire display bezel area of a large display, such as the HIPerWall. The number of projectors necessary to cover the entire area mainly depends on the aspect ratio of the display. For the HIPerWall, which has an aspect ratio of 16:5, three regular, horizontally aligned projectors with an aspect ratio of 4:3 are necessary to maintain maximum vertical resolution. Some vertical pixel columns, however, will remain unused. With only two projectors, vertical resolution is somewhat lower, and some horizontal pixel rows will remain unused. The number of projectors therefore depends on the budget and on the desired resolution. A comparably small number of additional projectors is needed to cover a large number of monitors.

4 Examples

Provided with the enhanced tiled display wall, we wanted to investigate its benefits in different scenarios. When working on construction plans it is necessary to display components without distortions. Fig. 8 illustrates the results obtained when visualizing an engine block with different bezel strategies. With the offset approach, the drive shaft in Fig. 8(a) appears discontinuous and broken to the middle. While this is most obvious effect,



(a) (b) (c)

Fig. 9. *Human zoom* as a natural interaction metaphor with Tiled++, a) Context information is available by *stepping back*, b) Focus information is available by *stepping forward*, c) Shadow removal using multiple projectors

Fig. 10. A HIPerWall user enters the projection area from the right and casts a shadow on the Tiled++ projection (projector mounted too low).

further distortion artifacts among the components can easily be made out. Apparently the offset approach is not an adequate choice for visualizing proportion sensitive data. In Fig. 8(b) some artifacts are eliminated with the overlay approach. Distortion effects are not existent but still black bars traverse the scene and disturb perception. The Tiled++ approach in Fig. 8(c) outperforms the other two methods. Although bezels can still be made out by color and resolution, the information provided on the lattice and the absence of severe optical artifacts make our projection-based approach superior to the other two. Fig. 1 demonstrates how the overlay approach causes another serious problem that goes beyond the pure loss of information about the *geometry* of an object. While it is sometimes possible to deduce missing parts from the information remaining (based on experience and assumptions about the geometry), the hiding of *higher order* information is more severe. In the picture, the front area of a car coincides with a bezel bar of the display wall. Radiator and headlights are invisible. At the same time some other important information is missing - namely the emblem identifying the car. As a consequence, someone unfamiliar with cars will find it hard to determine the manufacturer, especially because the shapes of most todays car resemble each other. With Tiled++, this drawback is eliminated. The information provided on the lattice clearly identifies the car as a VW. Both examples show that without correction the image is either ambiguous or impossible to interpret. In most cases failure to correct for missing pixels leads to undesired results, loss of image information, or discontinuities. Tiled++ is compatible with a large number of application areas, ranging from medical imaging to engineering, from design to visual analytics, and from advertising to signage.

4.1 Interacting with the Tiled++ Display

Using projectors to project onto the bezels of LCD-based tiled walls seems to impose constraints to the possibilities of interacting with the displays. We explain how users navigate in front of a Tiled++ display and why interaction is not affected.

Multi-projector systems use *back projection* as a way to avoid shadowing when users move in front of the display. Having the possibility to come closer to the screen is important, since a primary goal of large displays is to support collaborative work. For obvious reasons back projection is not an option for Tiled++. With this, the problem arises that users enter the projection area and cast shadows on the silver screen lattice (Fig. 10). Note that only the bezels are affected by the shadow. The images displayed on the LCD panels of course remains the same.

The projector alignment described in section 3.2 is robust and allows inclined positions of up to 10 degrees between projectors and displays. Placing the projector collateral to the screen allows users to move in front of the displays at reasonable distances without shadowing the lattice.

This supports a habit we observed when users interact in front of large displays. Users wanting to have an overview of the scene step back in order to gain a larger field of view and be aware of context information. A more detailed view requires them to step forward so that they can focus on the object of interest. Physical movement in front of large displays is a natural focus + context technique we would like to refer to as *human zooming*. Tiled++ supports human zooming as follows: The low resolution information on the lattice is essential to perceive a seamless image from a "context distance" away from the monitors (Fig. 9(b)). When stepping forward, the extremely high resolution of LCDs becomes more important and allows to investigate details of a scene (Fig. 9(a)). The information on the lattice is not necessarily needed anymore, as its resolution is much lower than that of the LCDs.

Another option to minimize the effect of shadows is to overlay the projector image with a second projection from an opposite direction as illustrated in Fig. 9(c). Because the lattice is illuminated twice, users can touch the silver screen and still perceive information on it. Jaynes et al. [16] described a refined implementation of this idea using cameras to detect and remove shadows.

5 Evaluating the Tiled++ Approach

The examples given in section 4 show that Tiled++ is able to prevent loss of semantics and make presentation of information on multi-monitor systems appear more complete. Now we need to find out if our approach has an impact on how users are able to perform certain tasks using the enhanced display. We conducted a user study in order to quantify the effect of Tiled++ and compare it with the overlay and offset approach. We investigated users' performace in *navigation tasks* and *perception experiments*. We wanted to capture their personal opinion and asked them to complete a questionnaire.

Our main hypothesis was that the additional information provided by Tiled++ and the lack of image distortions positively affect user performance. We expected them in general to perform faster and more precise.

5.1 Experiment Design

The experiment was designed to investigate how users perform under the three different conditions. In navigation tasks we wanted to measure the users' performances in *dynamic* and *static* environments. We anticipated a difference in the value added to a scene when the environment is constantly changing (e.g. in an animation) or when it remains fixed during the task (e.g. when studying a map). Because we did not want to focus on a particular visualization technique, we kept tasks visually as simple as possible. For the static navigation experiment we chose a variant of the commonly known game **HotWire**. HotWire is a game of skill in which users have to move a mouse cursor along a predefined track without leaving an area of tolerance around it. We considered the game suited for our experiment because it forces users to navigate across monitor frames and explicitly deal with the advantages and disadvantages of the different approaches.

For the dynamic navigation task we decided to use a single player version of the classic **Pong** game. In this game a user has to return a ball bouncing of the wall with the help of a small paddle. We favored the game because it is simple to handle and uses diagonal motion, which could cause difficulties, as shown in section 2.1 (Fig. 2, Fig. 3 and Fig. 4). Control is limited to moving the mouse up and down, so that it does not require gaming skills at all to complete the task.

Whereas navigation tests were intended to provide objective and measurable data, we wanted to address the more subjective aspects when dealing with different approaches through perception experiments. We asked users to rate the difficulty of assigning collinear lines in a **Poggendorff** test and their satisfaction with the approaches when watching a short **animation**.

In the **questionnaire** presented at the end of the evaluation we asked users to rate their own performance and satisfaction with the approaches. One of the intentions with the questionnaire was to investigate whether there is a difference between the actual performance of an individual in a test (e.g. Pong) and its personal rating. Finally we wanted to find out if participants would use Tiled++ for themselves and what their suggestions for improving the Tiled++ approach are.

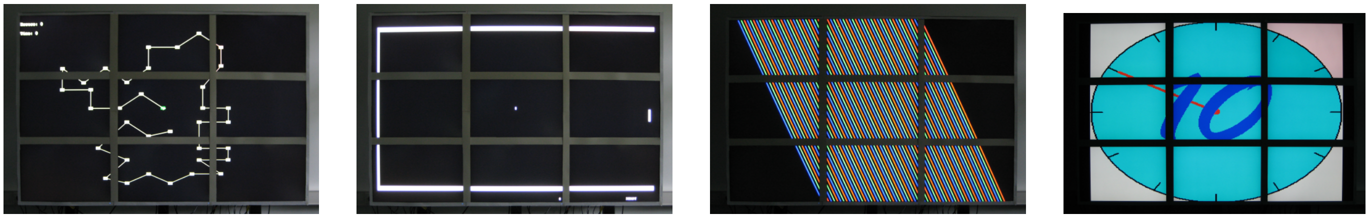
Participants had to pass each test three times - one time for each condition, which corresponds to one of our three approaches. In order to prevent learning effects and symptoms of fatigue, we permanently changed the order of approaches. Further we constantly altered the sequence of tracks presented in HotWire. The evaluation started with a mock-up explaining the general idea of experiments. Before starting a test, users received a verbal introduction and training for the application on a single monitor system. The whole evaluation took between 30 and 40 minutes per participant.

5.1.1 HotWire

This game follows the identically named game of skill from childhood days, in which a metal loop has to be directed along a curved wire without touching it. If the loop touches the wire the electric circuit closes and a small light will shine or a bell will ring indicating an error. Our version of the game works as follows:

A player has to direct a mouse cursor along a line strip without leaving a predefined area of tolerance around the track. The goal is to complete the course as *fast as possible* with as *few errors as possible*. The line strip is mixed with intermediate checkpoints that are unlocked as soon as a player passes them (i.e. they turn green). If the cursor leaves the track it will be reset to the last unlocked checkpoint. The player will be imposed with a time penalty of two seconds, in which he is not able to move on.

In the experiment the independent variable is the method being used expressed at three different levels (offset, overlay, Tiled++). The dependent variable is the time spent to complete the task. While running a game we measure the time and amount of errors that a subject



(a) (b) (c) (d)

Fig. 11. The navigation and perception tasks of the evaluation: a) HotWire, b) Pong, c) Poggendorff test, d) Animation test

made and record the locations where the tolerance area was left. Ideally a significant amount of errors will occur in the bezel region uncovering difficulties in navigating the cursor across the frames.

The game tracks were carefully designed with the following considerations: Every run of the game should involve a different track in order to prevent learning effects and their order should be constantly altered. Tracks should be of equal length and similar difficulty to make sure results are comparable. This was achieved by deriving each track from a given *template* by application of length-preserving geometric transformations such as mirroring and rotation. The template was subject to certain restrictions: We tried to avoid favoring a particular handedness of participants (i.e. left or right) by an almost circular design. Thereby we further achieved an uniformness of vertical and horizontal components, which is important since horizontal movements are often considered easier than vertical ones. Directional changes of line segments were restricted to predefined angles in order to generate more regular tracks. Additionally we defined maximal segment lengths so that quick walk-throughs by uncontrolled fast mouse drags are prevented. Fig. 11(a) depicts one of the levels.

5.1.2 Pong

Pong is based on the classic arcade game from the 1970s and works like a single player version of table tennis. A ball bouncing off the wall has to be returned with a small paddle (see Fig. 11(b)). We chose the game because it is very intuitive and can also be played by participants that normally do not play computer games. Further it is well suited for investigating how users deal with different bezel handling methods under dynamic conditions. In contrast to HotWire, Pong is permanently changing. The ball moves rather fast and users must try to estimate its movement in order to return it. This can be tricky when the ball rapidly jumps at the border of two monitors or vanishes under a bezel.

In our test each participant had ten attempts per approach. His task was to return the ball as *often as possible*. Again, the independent variable was the approach being applied expressed at three levels. As dependent variable we measured the total number of returns.

5.1.3 Poggendorff Experiment

The Poggendorff experiment is one of the perception tests we conducted with the participants. The probands did not have to perform under temporal or other restrictions. We asked them to freely investigate the problem and get an impression of what the advantages and drawbacks with the different approaches are. The questionnaire contained a number of questions addressing these aspects.

As stated in section 2.1, a problem with collinear oblique lines interrupted by parallel verticals is that they appear to be offset (see Fig. 4). The reason for this optical illusion is still not totally clear, however it directly affects visualization on tiled displays. Vertical bezels passing the display cause the same effect when using the overlay approach.

We set up a scene consisting of multiple oblique white lines running across all monitors. At the bezels users were asked to identify corresponding lines which proved to be rather hard considering the Poggendorff illusion. They could verify their decision by adding color to the scene and thereby identify corresponding lines by identic color as illustrated in Fig. 11(c). Naturally the effect does not arise with the offset approach since no information gets lets lost and distortions are directly due to the technique. Tiled++ prevents the effect because all lines appear continuous. However, we wanted to give users the possibility to get a feeling for the strengths and weaknesses of every method and asked them to complete the task with the other methods, too.

5.1.4 Animation Test

In the animation test a video sequence of a clock was presented to the users (see Fig. 11(d)) who had to rate their satisfaction with the different approaches in the questionnaire, afterwards. They should pay attention to how annoying image distortions with the offset approach are compared to the black bars of the overlay approach. Also the Tiled++ approach does not create a completely seamless image, because the different resolutions of the LCDs and the lattice are clearly visible.

5.1.5 Questionnaire

At the end participants had to fill out a questionnaire containing 16 questions. Seven of them were directly specific to the experiments, being of the kind ”How would you rate perceptual experience with the different approaches during test X?” or ”Do you think approach X improved your efficiency during test Y?”. Further questions referred to general impressions with Tiled++, comments for its improvement and statistical information about the participant for classification purposes. The selected group of participants was not a representative set of individuals, but rather a group of computer users.

5.1.6 Population

We asked 20 volunteers to participate in our study, 4 of them being female. Most participants were recruited from the computer science lab, so the average stated to have considerable knowledge with computers or at least be familiar with them. 6 were undergraduate students, the rest were graduate students. A majority claimed to use multi-monitor systems never or only rarely. 3 volunteers stated to regularly use them during work. The average age of participants was 29.3 (range was between 21 and 49).

5.2 Results

5.2.1 Findings from the Navigation Tasks

A one-way ANOVA (**A**nalysis **o**f **Va**riance) study was conducted with the data from the static and dynamic navigation task. Table 1 summarizes the average amount of time and errors for HotWire (static), including their standard deviations. We found the effect of approaches on *how fast* users complete the task was significant, $F_t(2,57) = 16.01$, $p_t < 0.001$. Tukey's HSD (**h**onestly **s**ignificantly **d**ifferent) post-hoc test revealed significant pairwise differences among the means of the offset and overlay methods and the overlay and Tiled++ methods, respectively. No significant difference could be attested for offset and Tiled++. The analysis of *error rates* coincides with these discoveries, i.e. $F_e(2,57) = 19.52$, $p_e < 0.001$.

The results were not completely unexpected. We anticipated that the overlay approach would cause the biggest problems when navigating across monitor bezels and that Tiled++ would perform best. Trying to reconstruct the missing information under the bezels appears to be harder than trying to compensate for the discontinuities of the offset approach. Further it seems natural that with the additional information provided by the projector, Tiled++ outperforms the overlay technique. The recordings of error positions show that with the overlay approach, 89% of errors occure at the bezels of the tiled display. However, we were surprised to find no significant difference between offset and Tiled++, and expected the discontinuities to have more severe effects on navigation. We conclude that the availability of the complete image information is the most important aspect for completing a given task in a reasonable time.

Data analysis of the dynamic navigation task (Pong) revealed no differences among means. Neither of the three

Approach	Mean time (s)	Standard deviation of time (s)
Offset	142,5	56.95
Overlay	263.15	142.40
Tiled++	109.05	33.25
	Mean error rate	**Standard deviation of errors**
Offset	15.95	16.02
Overlay	40.70	23.47
Tiled++	9.45	5.26

TABLE 1
Averages and standard deviations of performance time and error rates for HotWire

Approach	Mean # of returns	Standard deviation
Offset	10.1	6.99
Overlay	13.55	9.48
Tiled++	12.05	12.24

TABLE 2
Averages and standard deviations of returns for Pong.

methods performed significantly better than the others (see Table 2). This was surprising, since we expected the offset approach with its jumping ball to perform worst. Further we anticipated the additional information on the lattice would increase the user's ability to estimate the trajectory of the ball. We interpret the result as follows: In a dynamic and rapidly changing environment, the intensity of the bezel problem seems to decrease. A reason might be that users perceive the image more as a whole and do not concentrate so much on particular tiles and the transitions between them. Interestingly enough, a majority of participants anyway preferred Tiled++ in terms of perception. Fig. 12 depicts an extract from the questionnaire findings. Participants were asked to rate their experience with the different approaches for every task (1 = poor, 6 = excellent). Although the analysis of variance revealed no differences among means in terms of efficiency, users subjectively preferred the Tiled++ approach.

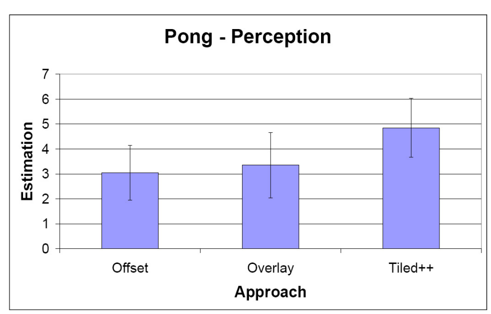
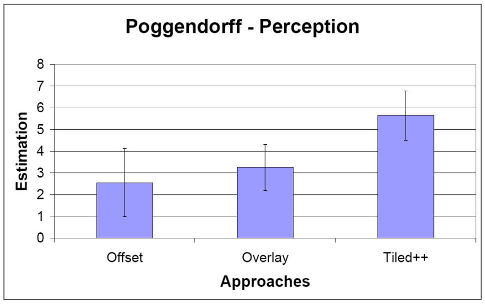


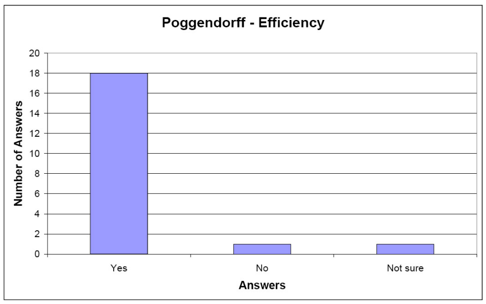
Fig. 12. Ratings of perception for Pong.

5.2.2 Findings from Perception Tasks

The Poggendorff illusion had a clear effect in our perception experiment. Participants stated to have moderate to high difficulties in assigning collinear lines at the vertical



(a)



(b)

Fig. 13. a) Rating of perception for the Poggendorff test. b) Rating of efficiency for the Poggendorff test.

borders of screens. This shows the effect cannot be ignored when designing applications for LCD-based tiled display walls. Offsets made the task generally harder. Some users figured out rules to systematically identify collinear lines with the offset approach (e.g. "If I want to find the corresponding line, I have to go two down and then to the right"). Thereby they were able to perform rather quickly, but discovering these rules took some time. Naturally the task was greatly simplified with the additional information on the lattice.

When being asked to rate perceptual experience and efficiency, participants answered as illustrated in Fig. 13. Perception with Tiled++ was rated highest with an average of 5.65 (1 = poor, 6 = excellent). The difference between overlay (3.25) and offset (2.55) was not significant. The efficiency rating shows that a majority of participants, about 90%, considers Tiled++ to increase performance.

Considering the perception rating of the video, we obtained the results depicted in Fig. 14. The approaches that do not distort the image were rated significantly higher than the offset approach. Tiled++ and overlay were on average rated 5.3 respectively 4.45, whereas offset was only rated 2.25. We think a reason for Tiled++ not being significantly better than the other two approaches is the missing adjustment of colors. As stated in section 3.2, calibration only considers the geometric alignment. Therefore, a transition between the lattice and LCDs is clearly visible. Our interpretation was mostly confirmed by the comments from the questionnaire.

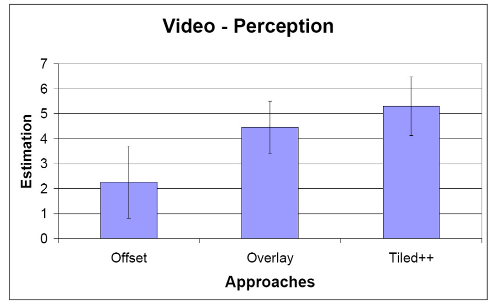


Fig. 14. Rating of perception for the video test.

5.2.3 Findings from the Questionnaire

Besides what has already been addressed in the previous sections, we asked participants to give earnest feedback about what they consider to be the major benefits and drawbacks of Tiled++. This information may be useful in future designs of tiled displays. The participants' comments may be summarized as follows:

The additional information on the lattice was throughout rated positively. Monitors were perceived as an almost seamless tiled display. Surprisingly, neither of the participants complained about the different resolutions of the projector and the LCDs. We considered them to be a major point of criticism, but apparently participants did not agree. A majority of 70% claimed they would use Tiled++ again, while 30% were not sure. Further, 90% considered Tiled++ to be a benefit for displaying information on tiled walls. 10% were unsure about the approach. Alltogether, the feedback was thoroughly positive.

A major point of criticism was the difference in brightness and color between the projector and the LCDs. This became clear during the video sequence. The video experiment was the only test in which users did not have to react and could take time to form an opinion. Therefore they could concentrate on aspects for which there was no time during the other experiments. We are going to take their critiques into account and will improve the perception of Tiled++ with an adequate adjustment of color and brightness.

6 Discussion

In multi-monitor systems display frames distort scenes or cover important parts of them. This leads to potential misinterpretation of image information, as we were able to show in the evaluation section. Static navigation tasks were seriously affected by the missing content of the overlay method, whereas dynamic navigation did not seem to suffer to the same extent from this problem. The results of the evaluation for example give rise to questions pertaining the use of tiled displays in safety-relevant applications such as flight control or other vital operations. Here, misinterpretation of image information can have severe consequences. However, the extremely high resolution of LC displays and their affordability make the use of tiled displays favorable.

We could show that it is possible to bypass the drawbacks of conventional tiled display techniques with minimal effort. Our hybrid approach combining different display technologies is able to produce an almost seamless tiled display avoiding discontinuities while at the same time maintaining a majority of pixel information. Installations on a 3×3 and 10×5 display cluster proved scalability and technical feasibility of the approach using standard display components. The idea is new to our knowledge and captivates by its pure simplicity. With this, Tiled++ is a contribution that adds to a very small set of methods that explicitly deal with the bezel problem.

The examples we provided demonstrate that the approach is not limited to certain application fields. Collaborative work is supported by the way in which users can interact in front of the display without disturbing the scene (see section 4.1). We can think of Tiled++ being used for large scale design studies in architecture or mechanical engineering as well as in the context of decision processes in urban planning and development. In our study, users primarily benefited from the additional information we provided and almost consistently preferred our hybrid approach over a standard tiled display. The questionnaire helped us in making out minor flaws. Especially the difference in color and luminance between the projectors and LCDs was criticized in the perception ratings. In the future we are going to apply existing multi-projector calibration techniques to solve this problem.

7 Conclusion and Future Work

We presented Tiled++, a new and scalable approach that addresses the bezel problem of LCD-based tiled displays. Tiled++ uses projectors to enhance monitor frames with image information that is usually lost (overlay) or deformed (offset). We set up both a 3×3 and a 10×5 prototype that can be used in a variety of application fields (e.g. scientific and information visualization). In the evaluation section we tested the performance of 20 participants in navigation and perception tasks. We found that Tiled++ had a positive influence and made participants in general perform faster. Issues going in hand with image deformations or missing image contents are not present anymore.

In the future we plan to refine the calibration of Tiled++, especially in terms of color and brightness. Adapting existing techniques from the area of multi-projector systems seems promising to push ahead our hybrid approach combining two different display technologies.

Acknowledgments

This work was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG, grant number 1131) as part of the International Graduate School (International Research Training Group, IRTG) in Kaiserslautern, Germany. The authors would like to thank Jan Malburg (University of Applied Sciences, Saarbruecken) for his technical support during the project. Further thanks go to Stephen Jenks and Sung-Jin Kim (University of California, Irvine), Falko Kuester and Kai-Uwe Doerr (University of California, San Diego) and the National Science Foundation for their support of the HIPerWall research project.

References

[1] R. Ball, M. Varghese, B. Carstensen, E. D. Cox, C. Fierer, M. Peterson, and C. North, "Evaluating the benefits of tiled displays for navigating maps," in *IASTED International Conference on Human-Computer Interaction*, 2005.

[2] R. Ball and C. North, "Effects of tiled high-resolution display on basic visualization and navigation tasks," in *CHI '05: CHI '05 extended abstracts on Human factors in computing systems*. New York, NY, USA: ACM, 2005, pp. 1196–1199.

[3] ——, "Visual analytics: Realizing embodied interaction for visual analytics through large displays," *Comput. Graph.*, vol. 31, no. 3, pp. 380–400, 2007.

[4] J. P. Birnholtz, T. Grossman, C. Mak, and R. Balakrishnan, "An exploratory study of input configuration and group process in a negotiation task using a large display," in *CHI '07: Proceedings of the SIGCHI conference on Human factors in computing systems*. New York, NY, USA: ACM, 2007, pp. 91–100.

[5] D. S. Tan, D. Gergle, P. G. Scupelli, and R. Pausch, "Physically large displays improve path integration in 3d virtual navigation tasks," in *CHI '04: Proceedings of the SIGCHI conference on Human factors in computing systems*. New York, NY, USA: ACM, 2004, pp. 439–446.

[6] E. Moritz and J. Meyer, "Interactive 3d protein structure visualization using virtual reality," in *BIBE '04: Proceedings of the 4th IEEE Symposium on Bioinformatics and Bioengineering*. Washington, DC, USA: IEEE Computer Society, 2004, p. 503.

[7] T. Wischgoll and J. Meyer, "Navigational aspects of an interactive 3d exploration system for cardiovascular structures," in *VIIP 2005: International Conference on Visualization, Imaging, and Image Processing, Benidorm, Spain*, 2005, pp. 721 – 726.

[8] T. Ni, G. S. Schmidt, O. G. Staadt, R. Ball, and R. May, "A survey of large high-resolution display technologies, techniques, and applications," in *VR '06: Proceedings of the IEEE conference on Virtual Reality*. Washington, DC, USA: IEEE Computer Society, 2006, p. 31.

[9] A. Majumder and M. S. Brown, *Practical Multi-projector Display Design*. Natick, MA, USA: A. K. Peters, Ltd., 2007.

[10] R. Sukthankar, R. G. Stockton, and M. D. Mullin, "Smarter presentations: exploiting homography in camera-projectorsystems," in *Computer Vision, 2001. ICCV 2001. Proceedings. Eighth IEEE International Conference on*. Washington, DC, USA: IEEE Computer Society, 2001, pp. 247–253 vol.1.

[11] H. Chen, R. Sukthankar, G. Wallace, and K. Li, "Scalable alignment of large-format multi-projector displays using camera homography trees," in *VIS '02: Proceedings of the conference on Visualization '02*. Washington, DC, USA: IEEE Computer Society, 2002, pp. 339–346.

[12] Y. Chen, D. W. Clark, A. Finkelstein, T. C. Housel, and K. Li, "Automatic alignment of high-resolution multi-projector display using an un-calibrated camera," in *VIS '00: Proceedings of the conference on Visualization '00*. Los Alamitos, CA, USA: IEEE Computer Society Press, 2000, pp. 125–130.

[13] M. C. Stone, "Color and brightness appearance issues in tiled displays," *IEEE Comput. Graph. Appl.*, vol. 21, no. 5, pp. 58–66, 2001.

[14] A. Majumder, Z. He, H. Towles, and G. Welch, "Achieving color uniformity across multi-projector displays," in *VIS '00: Proceedings of the conference on Visualization '00*. Los Alamitos, CA, USA: IEEE Computer Society Press, 2000, pp. 117–124.

[15] A. Majumder and R. Stevens, "Perceptual photometric seamlessness in projection-based tiled displays," *ACM Trans. Graph.*, vol. 24, no. 1, pp. 118–139, 2005.

[16] C. Jaynes, S. Webb, R. M. Steele, M. Brown, and W. B. Seales, “Dynamic shadow removal from front projection displays,” in *VIS '01: Proceedings of the conference on Visualization '01*. Washington, DC, USA: IEEE Computer Society, 2001, pp. 175–182.
[17] R. Sukthankar, T. Cham, and G. Sukthankar, “Dynamic shadow elimination for multi-projector displays,” in *2001 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'01) - Volume 2*. IEEE Computer Society Press, 2001, p. 151.
[18] J. D. Mackinlay and J. Heer, “Wideband displays: mitigating multiple monitor seams,” in *CHI '04: CHI '04 extended abstracts on Human factors in computing systems*. New York, NY, USA: ACM, 2004, pp. 1521–1524.
[19] P. Baudisch, E. Cutrell, K. Hinckley, and R. Gruen, “Mouse ether: accelerating the acquisition of targets across multi-monitor displays,” in *CHI '04: CHI '04 extended abstracts on Human factors in computing systems*. New York, NY, USA: ACM, 2004, pp. 1379–1382.
[20] P. Baudisch, N. Good, and P. Stewart, “Focus plus context screens: combining display technology with visualization techniques,” in *UIST*, 2001, pp. 31–40.
[21] C. Ware, *Information Visualization: Perception for Design*. San Francisco, CA, USA: Morgan Kaufmann Publishers Inc., 2004.

Achim Ebert is an Assistant Professor with the University of Kaiserslautern, Germany, since 2005. Dr. Ebert is also the head of the competence center Human-Centered Visualization at the German Research Center for Artificial Intelligence (DFKI GmbH) in Kaiserslautern, Germany. He received his Ph.D. from the University of Kaiserslautern, Germany, in 2004. His research interests include human computer interaction, information visualization, virtual and mixed reality, and mobile visualization.

Sebastian Thelen received a masters degree in computer science from the Technical University of Kaiserslautern, Germany, in 2007. He is a Ph.D. candidate in the Visualization Department. His research interests include new visualizations and interaction techniques for large high-resolution displays.

Peter-Scott Olech received a masters degree in spatial and environmental planning from the Technical University of Kaiserslautern, Germany, in 2007. He is a Ph.D. candidate in the Visualization Department and member (collegiate) of the IRTG. His research interests are in the field of information visualization and human computer interaction with new display technologies.

Joerg Meyer is currently an Assistant Professor at the University of California, Irvine. He has a shared appointment with the Department of Electrical Engineering & Computer Science and the Department of Biomedical Engineering. He is also affiliated with the California Institute for Telecommunications and Information Technology, Calit2. Prof. Meyer received his doctoral degree from the University of Kaiserslautern in 1999.

Hans Hagen received his B.S. and M.S. degrees from the University of Freiburg and a Ph.D. degree from the University of Dortmund. He is currently a professor in the Department of Computer Sciences at the University of Kaiserslautern, Germany, and is heading the research group for Computer Graphics and Computer Geometry. He is both a national and international pioneer in his research domains of Geometric Modeling and Scientific Visualization. Additionally, his scientific interests cover the domains of Computer Graphics and Computer Aided Geometric Design. His scientific work covers more than 250 refereed publications and 15 book titles.